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FEASIBILITY STUDY

CONSISTING OF

A REVIEW OF CONTOUR GENERATION

METHODS FROM STEREOGRAMS

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A Review of Contour Generation from Stereograms

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Abstract

A review of techniques for obtaining contour information from stereo pairs is given. The report begins with a review of photogrammetric principles including a description of stereoscopic vision. The use of conventional contour generation methods, such as the photogrammetric plotting technique, electronic correlator, and digital correlator are described. Coherent optical techniques for contour generation are discussed and compared to the electronic correlator. The optical techniques are divided into two categories: (1) image plane operation and (2) frequency plane operation. The description of image plane correlators are further divided into three categories: (1) image-to-image correlator, (2) interferometric correlator, and (3) positive-negative transparencies. The frequency plane correlators are divided into two categories: (1) correlation of Fourier transforms, and (2) filtering techniques.

A REVIEW OF CONTOUR GENERATION METHODS FROM STEREOGRAMS

This report gives a review of techniques for obtaining contour information from stereo pairs. The report begins with a review of photogrammetric principles. The review is followed with a description of conventional or classical methods for analyzing stereo pairs. The last part of the report reviews stereo contouring techniques using coherent light.

I. Photogrammetric Consideration

A. Stereoscopic Vision

To gain an understanding of the way a person can see stereoscopically by viewing a pair of photographs taken from two viewpoints, refer to Fig. 1. In Fig. 1, two dots of similar size and shape have been drawn on a sheet of paper about 2 in. apart. If the viewer looks downward from a height above the paper between 12 and 15 in. and can make the left eye concentrate on the left dot and the right eye on the right dot, he forms a single image of the two dots at some distance d_1 from the eye. The conjugate image to the right and left are not seen distinctly, since they are out of range of critical resolution of the eyes. The impression of the distance d_1 is gained because of the parallactic angle ϕ_1.

B. Parallax

The spatial relationship between the two photographs forming the stereo pair and the three-dimensional object is illustrated in Fig. 2. This figure refers to the simple and ideal case of vertical photographs, in which the camera axes are parallel to each other and perpendicular to the reference plane. The transparency is a positive print of the negative and is located

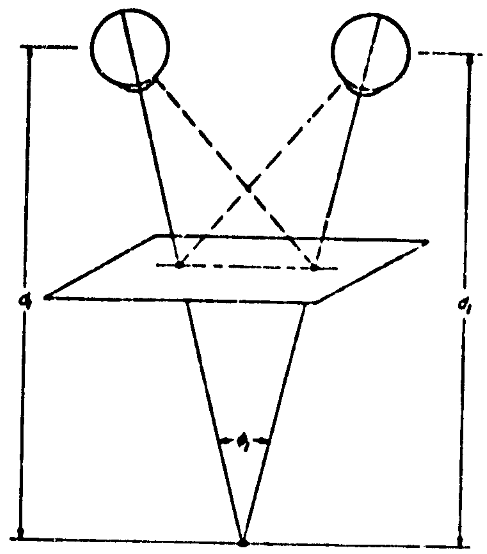

Fig. 1. Stereoscopic Vision.

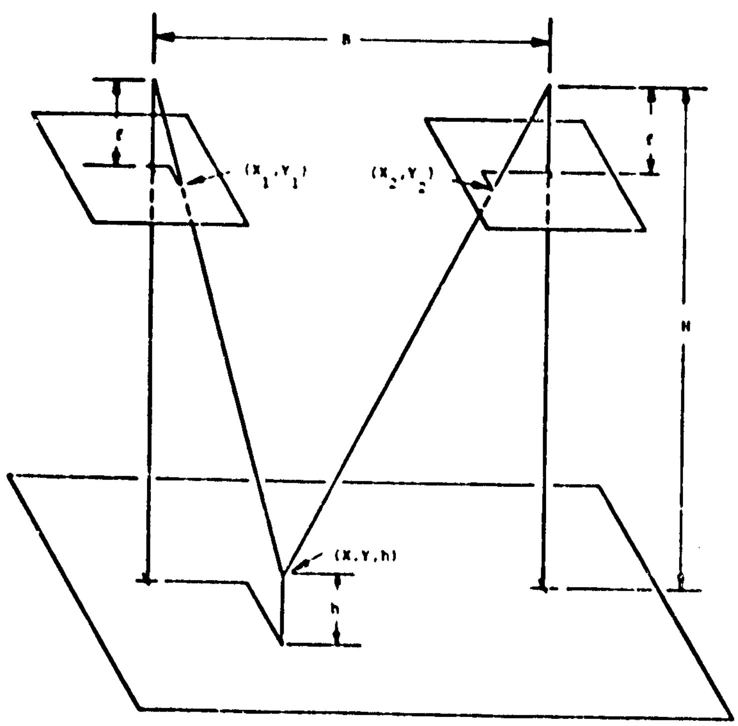

Fig. 2. Stereoscopic parallax for vertical photographs.

symmetrical to the negative about the perspective center (the camera lens). The distance f is equal to the focal length of the lens for distant objects. The separation B is defined as the stereo base. Using similar triangles,

$$X_1 = fX/(H-h)$$

$$X_2 = f(X-B)/(H-h)$$

$$Y_1 = Y_2 = fY/(H-h)$$

The x-parallax P_x is defined as

$$\begin{aligned} P_x &= X_1 - X_2 \\ &= fB/(H-h) \\ &\cong fBh/H^2 \qquad \text{(if } H \gg h) \end{aligned}$$

As the object height h varies from object point to object point, the x-parallax also changes and the x-parallax differences are the principal cause of stereo perception.

II. Conventional Methods

A. Photogrammetric Plotting Technique

This method depends on the stereoscopic vision of a human observer. A fictious stereo model is generated from two diapositives by projection. The concept is illustrated in Fig. 3. The diffusing disc in Fig. 3 is called a platen. If the conjugate images projected by the two projectors are received on the platen surface, and if the operator views the platen, he will see a double image of the terrain features.

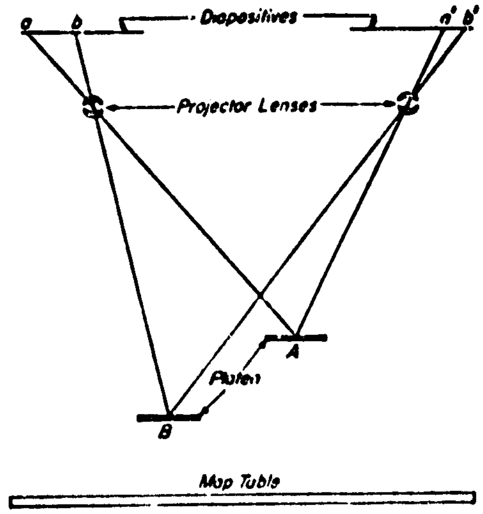

Fig. 3. Coincidence of double images at different platen heights.

In order that the model may be seen stereoscopically, one of the images must be seen with one eye only while the other image is seen with the other eye only. Usually the color filters are used for discrimination.

With the aid of a self-illuminating dot at the center of the platen, the operator can follow the terrain where the measuring dot is contact with the surface of the stereo model. This stereo compilation process is tedious and time-consuming.

B. Electronic Correlator

All automated stereo-compilation instruments are based on the ability to match conjugate images and automatically determine the parallax differences from object point to object point. The matching of conjugate images involves the examination of the similarity of the spatial density variations corresponding to the conjugate images. This is the process that is referred to as cross-correlation.

In an electronic correlator, the optical transmittances of the two transparencies are converted to electrical signal by the use of a CRT flying spot scanner (FSS). The FSS scans a small portion of each transparency at the same time. The system is illustrated in Fig. 4.

Thus if the optical transmittance functions of the two transparencies are denoted by $T_1(x,y)$ and $T_2(x+\Delta x,y)$ where Δx represents the displacement in the x direction, then $T_1(x,y)$ becomes $I_1(t)$ in the time domain and $T_2(x+\Delta x,y)$ becomes $I_2(t+T)$ where T is the delay time. These two signals are fed into an electronic correlator whose output provides information regarding image matching. If the images are not matched the value of Δx is changed and thus T is changed until correlator detects image matching.

C. Digital Correlator

A digital correlator is similar to an electronic correlator. It uses scanning system to get the density information of the stereograms. However, the density at each resolution element of each photograph is scanned and measured only once for correlation operations. This is in contrast to scanning a resolution element each time its value is needed to perform a correlation operation like an electronic correlator. The system ability to operate with a single measurement of each resolution element depends upon digital image storage and accessing through address modification. Once a resolution element is measured, its density value is stored (digitally) and accessed as needed for correlation operations. Measuring each image element only once increases the system speed potential compared to that of an electronic correlator. Furthermore, by using digital filtering before the correlation operation, the correlation signal can be enhanced.

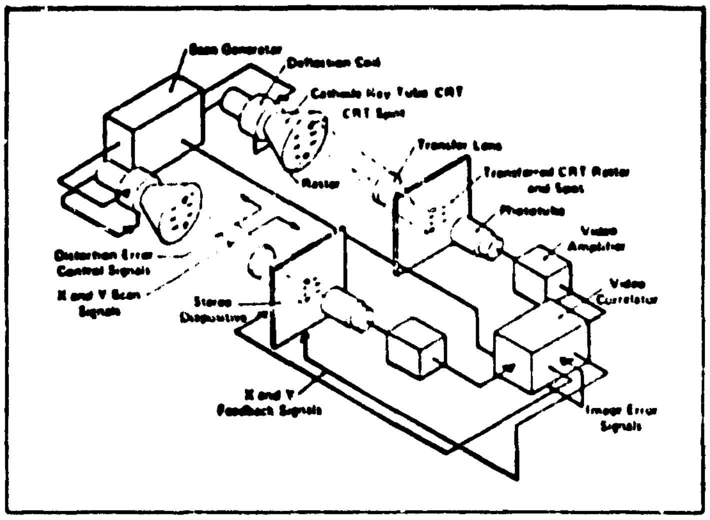

Fig. 4. Basic Electronic Correlation System.

A digital correlator with the same accuracy as an advanced electronic correlator but with the speed of at least ten times faster has been developed by Bendix Research Laboratory (Ref. 1).

III. Coherent Optical Methods

A. Advantage of Optical Method

The optical correlators have better performance factors than the electronic correlator (Ref. 2). These performance factors are bandwidth, signal-to-noise ratio in detection, complexity, and speed. The bandwidth of coherent optical systems is flat out to a signal frequency that is determined by the optical system and not the electronics. In most cases, this cut-off frequency is higher than the bandwidth of the equivalent electronic correlator. In an electronic correlator the noise is produced by the electronics during and after the correlation. However, in an optical correlator the noise is produced after the correlation is performed. Because optical correlator systems

perform the correlation using light, it is possible to perform the correlation over the whole area at any instant of time rather than on a small segment as is required in an electronic correlator. Also, the optical correlators do not need computing electronics for correlation. This results in a decrease of complexity in the equipment needed and an increase in the rate that the information can be gathered. While in the electronic correlation systems only the spatial frequency information along one direction is used in the image matching process, in the optical correlation systems the two-dimensional spatial frequency information is used in the image matching process.

B. Image Plane Operation

1. Image-to-Image Correlator. If one transparency of the stereo pair is imaged on the other transparency, the effective transmittance is the product of the two transmittances. If this effective transmittance is Fourier transformed by a lens, the signal at the focal plane is the correlation of the Fourier transforms of the two transmittances. Therefore, if the transmittances are matched, the correlation becomes autocorrelation and has its peak on the axis. This property is used to find the coincidence of the areas.

a. Scanning-type. This method is basically similar to the electronic correlator. The system is illustrated in Fig. 5. Only a small section of the transparencies is illuminated at one time and one transparency is moved until the correlation signal becomes a maximum. This process is then repeated on the other sections of the transparencies. So the transparencies should be scanned and thus one of the advantages of using an optical correlator is lost, i.e., the ability to perform a correlation over the whole surface at the same time. The accuracy of this system depends on how small a portion of the transparencies can be analyzed. The product of the sampled area and spatial frequency bandwidth (space-bandwidth) should be maintained large.

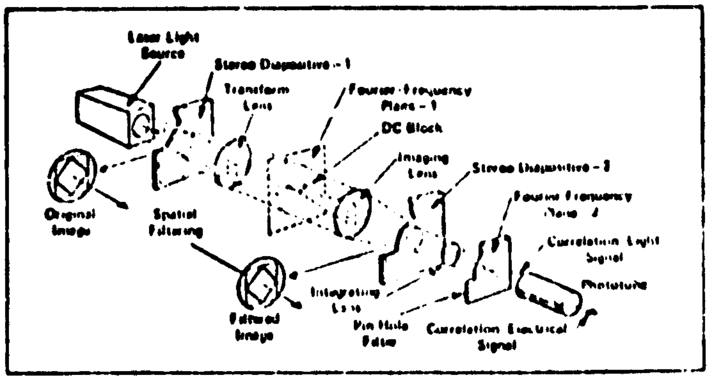

Fig. 5. Scanning-type Image-to-Image Correlator.

b. Scatter-plate system. This contour extraction system is based on the principles of the scatter-plate interferometer (Ref. 3). The system is illustrated in Fig. 6. A coherent plane wave illuminates the first transparency and the scene structure diffracts light around the D.C. block in the first Fourier plane. If a portion of the second transparency is identical to the first, some of the light is rediffracted into a collimated beam, and this is focused through the pinhole in the second Fourier plane, and passed on the final plane.

From the image-to-image correlation view, the correlation at the second Fourier plane becomes the autocorrelation for the matched areas. The autocorrelation signal has its peak on the optical axis, so it easily passes through the pinhole. However, for the mismatched areas the correlation becomes the cross-correlation and its signal on axis is very low.

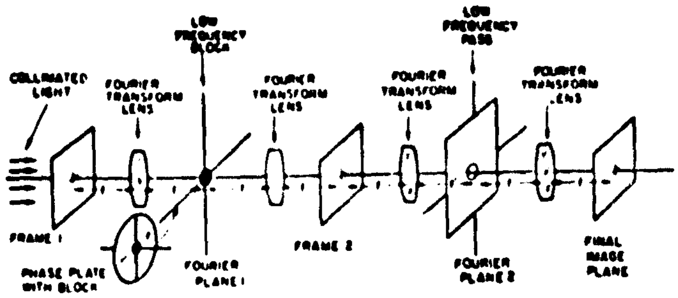

Fig. 6. The Scatter-Plate Processor.

A significant sharping of the contours is achieved by adding a half waveplate in the first Fourier plane. The combined block and phase plate cause the output amplitude to go zero precisely at the center of the contour.

Because the pinhole passes only the low frequency term, the contour widths are wider, and hence less accurate than corresponding widths from stereo plotting devices.

c. Phase holograms. This method uses the property of a hologram that the reconstructed objective wave is identical to the original object wave only when the reconstruction reference wave is identical to the reference wave used to make the hologram and the intensity of the reference wave is constant (Ref. 4). Mathematically, if O is the objective wave, R is the reference wave, and I is the reconstructing reference wave, then the important term is ORI*

$$ORI^* = O|R|^2 \qquad \text{(if } R=I\text{)}$$

$$= CO \qquad \text{(if } |R|^2 = C\text{)}$$

This property of a hologram is utilized by bleaching the two transparencies so that the density transmittances are converted into the phase transmittances and the density transmittances become constant. The system is illustrated in Fig. 7.

An image plane hologram is made of one of the bleached transparencies using a plane wave as object wave. When the hologram is reconstructed, the transparency used to make the hologram is replaced by the other bleached transparency. Only in those regions on the hologram where the phase of the light from the two stereo transparencies are identical will the reconstructed wave propagate in the direction of the plane wave used to make the hologram.

A lens is used to image the hologram and a small hole is located at the focal plane. Then only the light propagating in the direction of the plane object wave will pass the hole and illuminate the image plane. Mathematically, for matched areas the reconstructed wave at the focal plane becomes the autocorrelation of the Fourier transform of the phase transmittance and has its peak on the axis. So it will easily pass the small hole.

The problem of this system as well as all other imaging systems with a small hole is that the final image is convolved with the Fourier transform of the hole. So it can not resolve the narrower contours. To increase resolution, the size of the hole should be increased. However the diameter of the small hole is limited by the diffracted light from the mismatched areas. To decrease this light the amplitude of the phase variation should be increased. But it is limited by the repeatability of the process.

2. Interferometric correlator. If the amplitude transmittances of two transparencies are added coherently, the superimposed intensity image distribution is given by

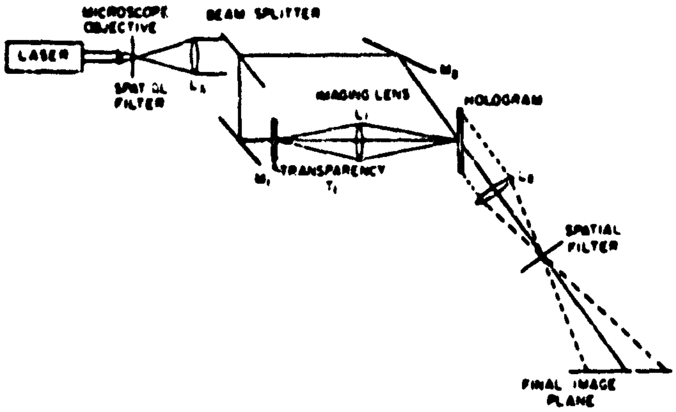

Fig. 7. Phase Hologram Correlator.

$$I(x,y) = |T_1(x,y)|^2 + |T_2(x,y)|^2 + 2T_1(x,y)T_2(x,y)\mathrm{Cos}(\phi(x,y))$$

where $\phi(x,y)$ is the phase difference distribution between the two beams at the final image plane. It is clear that the coherent addition of the amplitude transmittances of two transparencies gives rise to a term containing the product of the amplitude transmittances at the superimposed intensity distribution. The independent detection of this term forms the basis for the interferometric correlator.

a. Measuring visibility. This system illustrated in Fig. 8 essentially consists of a Mach-Zehnder interferometer and two x-y photo-carriages which hold the stereo-transparencies in each channel of the interferometer. The stereo-transparencies are then spatially filtered to remove the average transmittance from the stereo images. The filtered images are then super-imposed at the output of the interferometer, and the regions of conjugate image coincidence at the superimposed image plane are detected through the existence of fringe modulation in those areas.

By translating one transparency with respect to the other, different conjugate image areas can be made to coincide and the magnitude of translation

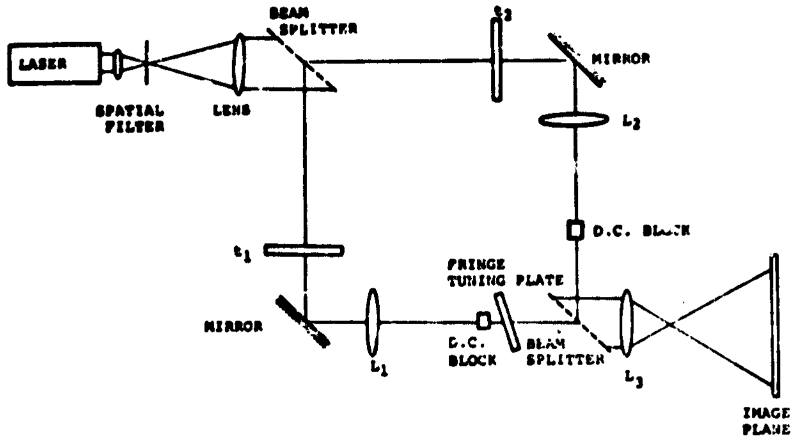

Fig. 8. Interferometric Correlator.

then represents the parallax between the transparencies. Because it is necessary to detect the existence of fringes for matching the conjugate images, the system gives poor spatial and height resolution. If the fringes are made finer in order to increase the spatial resolution, the measurement of the fringe contrast becomes more difficult (Ref. 5).

b. Making grating. In this method, two identical two-lens enlarging projectors, offset from one another while sharing the same coherent source of illumination are used to produce straight fringes (Ref. 6). If a photographic plate is exposed in the common image plane and developed, a grating is formed only on the regions that have image coincidence. If the processed plate is now illuminated by a coherent collimated beam of light, the light will be diffracted only in the image coincidence regions. If an observer views the plate from the appropriate off-axis angle, he will see an equal height contour. The disadvantage of this method is the necessity of exposing and developing a separate photographic plate for each contour.

c. Heterodyne technique. One of the reasons the visibility-measuring method fails is that the contrast of stationary fringes is used to

detect image coincidence. By using scanning fringes, the resolution can be improved. The fringe contrast at any point is measured as the amplitude fluctuation of the intensity at that point. The system is illustrated in Fig. 9.

In this case, it is possible to define a normalized correlation coefficient whose value is determined by the measurement of the intensity signal.

The intensity distribution at the superimposed image plane is given by

$$I(x,y) = |T_1|^2 + |T_2|^2 + 2T_1T_2\mathrm{Cos}[k(\Delta\omega t+\Delta_1(x,y) - \Delta_2(x,y))]$$

where Δ_1 and Δ_2 represent the path difference distribution of the two beams at the image plane and $\Delta\omega$ is the frequency shift. A detector of aperture A is placed at the point (x,y) in the image plane. The fringe spacing due to phase difference is arranged to be large enough such that the phase difference over the detector area is constant.

$$\Delta_1-\Delta_2 = \Delta_0 \quad \text{(a constant over the aperture of the detector)}$$

Hence, the time varying part of the photocurrent is given by

$$I_{ac} = 2K\mathrm{Cos}(k(\Delta\omega t+\Delta_0))\iint_A T_1T_2 dA ,$$

where K is a constant. If the beam of light from transparency 1 alone is used to illuminate the photodetector, then the value of D.C. photocurrent is

$$I_1 = K\iint_A T_1{}^2 dA$$

Similarly for the transparency 2

$$I_2 = K\iint_A T_2{}^2 dA$$

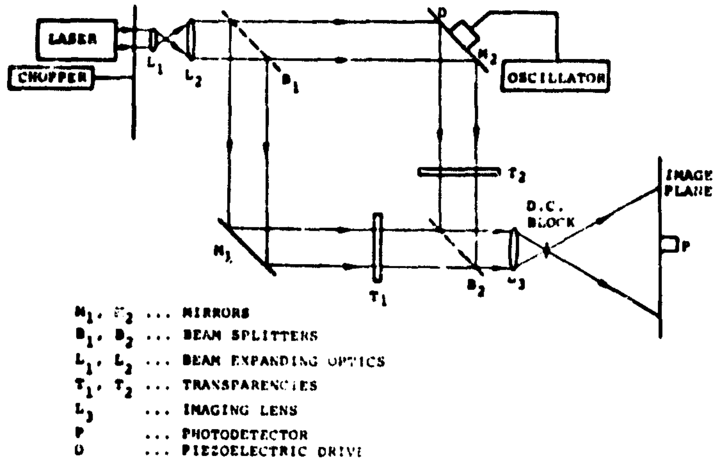

Fig. 9. Optical heterodyne correlator.

Now, the normalized correlation coefficient is defined by

$$C_{12} = 2 \iint_A T_1 T_2 dA / [\iint_A T_1^{\,2} dA \iint_A T_2^{\,2} dA]^{\frac{1}{2}}$$

The normalized correlation coefficient has its maximum value 2 when the area $T_1(x-s,y) = cT_2(x,y)$, where c is a constant, is directly over the region of the detector. Since T_1 can equal T_2 to within a multiplicative constant, it is seen that the different exposure levels for the two transparencies are of no consequence. Also, this system needs a constant optical path difference only over the aperture of detector, so the tolerance requirements on the optics of the system are minimal. This system also can handle the non-vertical stereo pair (Ref. 7).

3. Positive-negative. This method uses a positive transparency from one of the stereogram pair and a negative transparency from the other (Ref. 3). It assumes that the copies are made within the straight line portion of the H&D curve, where the slope is defined as the coefficient γ. If the gammas of the two copying process are equal in magnitude but opposite in sign, the product of the copies loses all its structural detail when the image matches exactly.

Mathematically,

$$T_a(x,y) = K_a[T_1(x,y)]^{-\gamma_a}$$

$$T_b(x,y) = K_b[T_2(x,y)]^{-\gamma_b}$$

$$T_aT_b = K_aK_b[T_1(x,y)]^{-\gamma_a}\ [T_2(x,$$

$$= K_aK_b[T_1(x,y)]^{-\gamma_o}\ [T_2(x,y)]^{-\gamma_o} \qquad (\text{if } \gamma_a=-\gamma_b=\gamma_o)$$

$$= K_aK_b \qquad (\text{if } T_1=T_2)$$

The isolation of this uniform, structure-free region depends on its contrast with the surrounding mismatched areas. This system works with either coherent or incoherent illumination. However, with a D.C. block in the frequency plane, the structure-free regions produce dark contours which are visually much easier to locate. The system is illustrated in Fig. 10. To change the contour level, the operator moves frame 2 in the direction of the parallax across the image of frame 1 in real time. The disadvantage of this process is the necessity for making copies of the input transparencies.

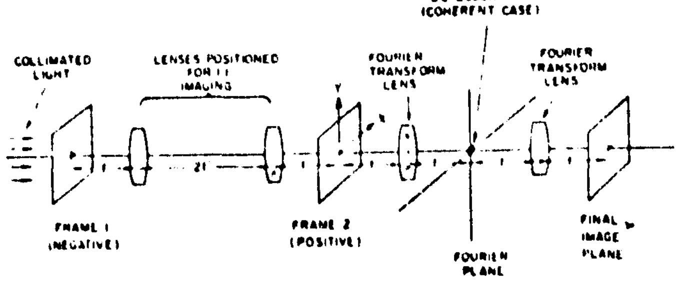

Fig. 10. The Positive-Negative Processor.

C. Frequency Plane Operation

<u>1. Correlation Method</u>. In the image plane correlator, the correlation of the Fourier transforms of the two transmittance functions is used. In the frequency plane correlator, the direct correlation of the two transparencies is used to find matching. Here the property of the hologram to storage amplitude and phase and the Fourier transform capability of a lens are used.

First, a Fourier transform hologram is made with one of the stereo pair and a plane wave reference. Then, when reconstructing the hologram, the transparency used to make the hologram is changed with the other transparency. Mathematically, the important term is $R_1 \cdot \tilde{T}_1^* \cdot \tilde{T}_2$ where R is the reference plane wave and $\tilde{T}_1$ and $\tilde{T}_2$ are the Fourier transform of the two stereo pair. If a lens is used to Fourier transform the reconstructed wave, the signal on the final image plane becomes the correlation of the two transmittance functions and the reference wave helps to separate this correlation signal from the other signals.

a. Parallel processing (one-dimensional matched filter). This correlator uses a one-dimensional Fourier transform hologram to display the parallax information along a strip simultaneously (Ref. 8). The optical arrangement is illustrated in Fig. 11. Through the combination of cylindrical and spherical lenses, a one-dimensional Fourier transform hologram is made of one of the transparencies. The x-coordinate that is Fourier transformed contains the parallax information. The y-coordinate is Fourier transformed twice and is imaged on the hologram. During reconstruction, a slit aperture such that the axis of the slit is along the y axis is placed over the second transparency. If the reconstructed wave that contains the correlation term is Fourier transformed one-dimensionally again, the y-coordinate of the image formed by the reference wave provides a convenient datum line. This system

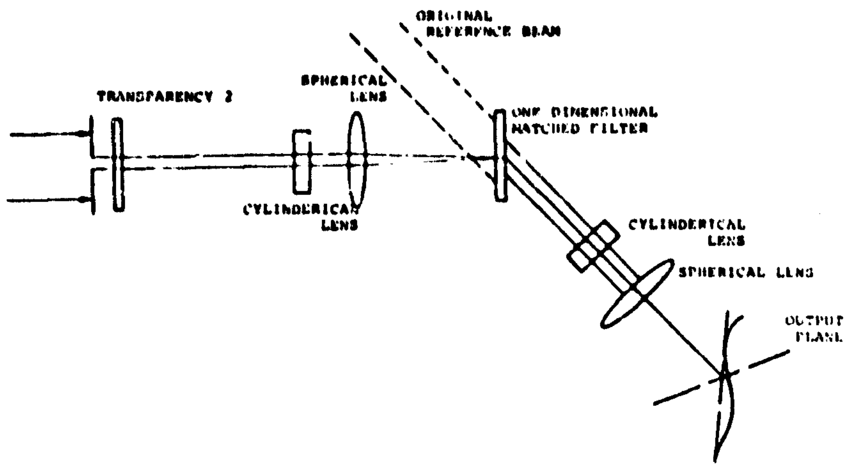

Fig. 11. One-dimensional profile generator.

uses only one-dimensional information, so it loses one of the advantages of the optical correlator.

b. Two-dimensional matched filter. This correlation system is a direct implementation of the basic concepts of the Vander Lugt filter and the typical optical arrangement is shown in Fig. 12. First, a two-dimensional Fourier transform hologram is made with one of the transparencies. Then, this matched filter is repositioned and the transparency is replaced with the other one. During reconstruction, the transparency is illuminated section-by-section and the reconstructed wave containing the correlation term is focused with a lens. The x and y coordinates of the peak correlation output signal represent the x and y parallaxes of that part of imagery on the transparency with respect to the conjugate imagery on the other transparency. This technique was used for aerial stereo photography (Ref. 9).

2. Filtering Method. The optical arrangement of this method is illustrated in Fig. 13. It uses a Mach-Zehnder interferometer in which the two transparencies are imaged on the common image plane. In the Fourier transform plane the parallax results in a grating-like structure that can be band-

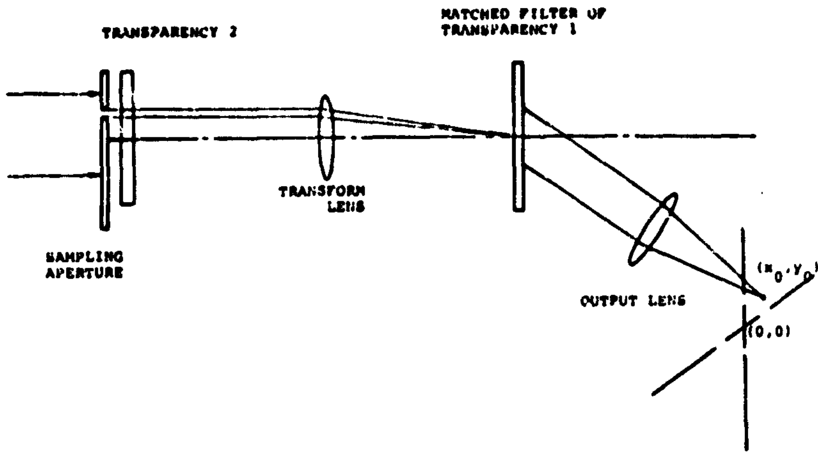

Fig. 12. Two-dimensional frequency plane correlator.

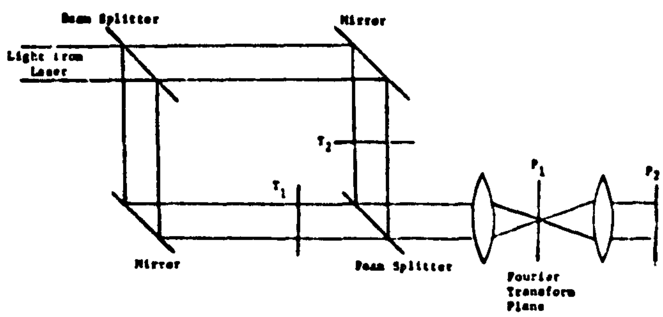

Fig. 13. Optical systems used to generate contours by filtering methods.

pass filtered in the Fourier transform plane to pass some given grating spacing and the corresponding parallax. A slit used for a bandpass filter is separated from the axis by some distance d. It passes each grating structure whose spacing is multiples of the distance d. So it generates several fringes simultaneously over a large range of the parallaxes. By changing the distance d, contours corresponding to different harmonics of the parallaxes can be generated. However, to pass a grating-like structure, the width of the slit should be small enough such that the grating-like structure should not vary over the slit aperture. Therefore, the maximum parallax that can be contoured is limited by the width of the slit. So this method is not suitable for a terrain with large parallax. On the other hand, the contour image is convolved with the slit so the width of each contour is spread out. Therefore the spacing of the contours should be large enough such that the spreading can be neglected. This means that the steepness of the terrain determines the width of the slit. So this method is not suitable for a terrain with high steepness. Furthermore, the stereo pair should have enough high frequency information (Ref. 10).

Another method is using a knife edge rather than a slit. Basically by inserting the knife edge in the Fourier plane the transmittance information is transferred into the phase information. With some approximations, this phase information is proportional to the parallax information. By interfering with a slowly varying reference wave, the phase change information after inserting the knife-edge gives the parallax information. To satisfy the approximations, first the parallax should vary slowly and should be small. Secondly, the transmittance should not vary much from the average value. This is an unusual limitation considering that all other methods require a large

variation of the transmittance. Third, the phase term that contains the parallax information should be linear to the parallax. This requirement can be satisfied only over the central region of the white area of a model with black dots over a white background. This method gives poor resolution (Ref. 11).

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